Beam Diagnostics in the SNS Linac

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Abstract. Most of the design work for the Spallation Neutron Source (SNS) linac beam diagnostics instrumentation is complete, and we are now entering the construction phase. Some instrumentation has already been delivered and tested at the Lawrence Berkeley Laboratory front-end systems tests. In this paper we will discuss the SNS linac beam diagnostics instrumentation designed by Los Alamos National Laboratory, and some of the early performance results. We will briefly mention the general layout of diagnostics in the SNS linac, then focus on two systems of special interest: the beam position monitors in the drift tube linac, and the wire scanner actuators in the superconducting linac.

INTRODUCTION

In the Spallation Neutron Source (SNS) facility, H⁻ beams are accelerated to 2.5 MeV in an RFQ, to 87 MeV in a drift tube linac (DTL), to 186 MeV in a coupled cavity linac (CCL), and finally to 1000 MeV in a superconducting linac (SCL). The 60 Hz, 1-ms, 36 mA peak current beam pulses are chopped into 690-ns long segments with a 1 μs period to give an average current of 1.4 mA and an average beam power of 1.4 MW.

The intense beam and the superconducting environment place special requirements on the beam diagnostics instrumentation [1,2]. Intercepting diagnostics cannot survive the entire 1-ms long beam pulse, especially at the lower beam energies. Diagnostics located nearby the superconducting RF cavities must also be ultra clean and highly reliable.

In the SNS linac there are beam position monitors (BPM), wire scanners (WS), beam current monitors (BCM), beam loss monitors (BLM), and energy degrader / Faraday cups (ED/FC), with quantities shown in Table 1. Also shown in Table 1 is the division of effort between Lawrence Berkeley National Laboratory (LBNL), Brookhaven National Laboratory (BNL), and Los Alamos National Laboratory (LANL). Laser-based profile monitors [3], in-line slit and collector emittance stations, and bunch shape monitors are also being developed.

The beam current monitor system is based on fast current transformers (FCT) from Bergoz Instrumentation, and custom built electronics. The electronics package uses the same PCI motherboard as the BPM system (see discussion below), but with a different analog front end, designed and fabricated by Brookhaven National Laboratory.

TABLE 1. Quantities of beam diagnostics devices in the SNS linac.

Device	MEBT	DTL	CCL	SCL	Resp. Lab
BPM	6[1]	10	12	32	LANL
WS	5[2]	5	10	32	LANL
BCM[3]	2	6	2	1	BNL
BLM		6	24	58	BNL
ED/FC		5	1		LANL

[1]Pickups designed and fabricated by LBNL.
[2]Pickups designed and fabricated by BNL.
[3]DTL and CCL BCM transformers supplied by LANL.

The beam loss monitor system [4] is also designed and fabricated by BNL. It is based on argon-filled ion chambers and custom built electronics packaged in VME modules.

The Energy Degrader / Faraday cup system, designed and fabricated by LANL, will be used to set the phase and amplitude of the DTL tanks. As shown in Fig. 1, each ED/FC unit has a graphite or copper plate of unique thickness in front of a Faraday cup. The plate, or "energy degrader", stops all the beam particles below a pre-determined cutoff energy suitable for a particular DTL tank. This ensures that a good phase and amplitude scan can be made without interference from beam particles that are not properly accelerated. To prevent contamination of the Faraday cup signal from secondary electrons a bias ring is located between the energy degrader and the Faraday cup. About –200 V will be sufficient to repel them. Graphite inserts are used in the Faraday cups to increase the maximum allowable beam power.
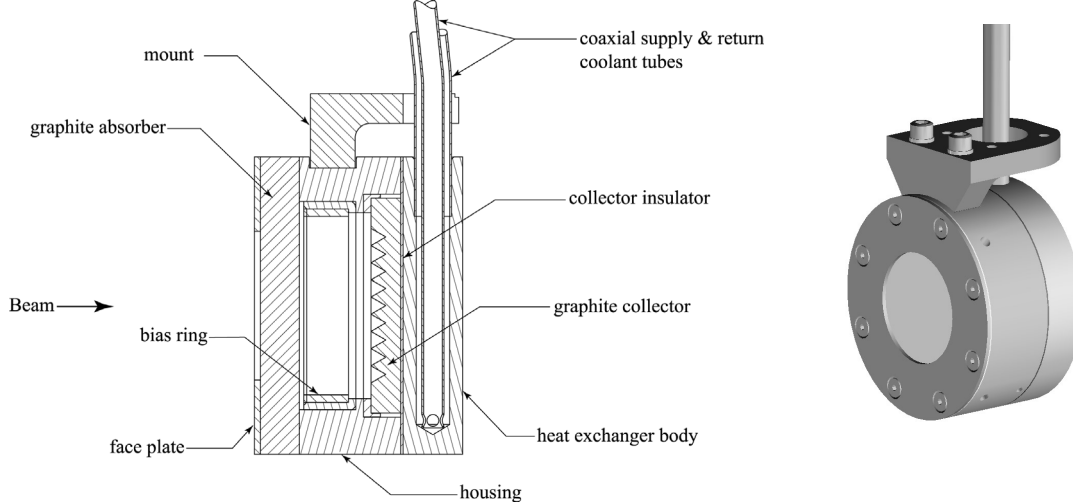

FIGURE 1. Images of an ED/FC unit. Left: cross section line drawing. Right: isometric image.

All the BPMs in the linac are of the dual-plane shorted-stripline design, with apertures varying between 25 and 70 mm diameter. The BPMs in the MEBT have 22° lobe angles to allow them to fit inside the quadrupole magnets. The CCL and SCL lobe angles span 45°, with the former located inside quadrupole magnets and the latter located toward the middle of each warm inter-segment region between the cryomodules. The DTL BPM pickups will be discussed in detail in the next section.

All the BPMs use the same electronics, which will also be discussed in detail in the next section.

The wire scanner actuators in the MEBT, DTL, CCL, and D-plate are based on linear actuators designed by LANL and purchased from Huntington Mechanical Laboratories, Inc. Each actuator fork has three 32-micron diameter carbon wires that can be biased to about ±100 V. The wires are offset by at least enough to ensure that there is only one wire at a time within ±2 rms of the beam center. The SCL wire scanner actuators will be discussed in detail in a later section.

In addition to all the above production diagnostics, a temporary Diagnostics Plate [1] is also being fabricated to commission the linac up to the end of DTL tank 1. The D-Plate diagnostics comprise three BPMs, one wire scanner, one BCM, one ED/FC, one view screen, an eight-segment halo scraper, a slit and collector emittance station, and a full power beam stop. Once the D-plate has fulfilled its function, which is expected to last about 90 days, it will be removed. Then DTL tank 2 will be installed in its place, and DTL commissioning will continue using only the production diagnostics permanently mounted in the DTL.

A diagnostic system of special interest is the DTL BPM system. The SNS is the first linac to incorporate BPMs inside DTL drift tubes. The SCL WS system is also of special interest because it employs actuators with formed bellows and a fork mounted on the end of a pivoting arm. These two systems will be discussed in detail in the following sections.

THE DTL BPM SYSTEM

The SNS DTL comprises six 402.5-MHz DTL tanks with FFODDO lattices. With this lattice there are many drift tubes without quadrupole magnets inside, thus permitting other uses for the empty drift tubes, such as steering magnets and BPMs. The inside bore of a drift tube is normally a smooth tube, with a length that gradually increases with beam energy. The DTL tank 1 drift tubes are too short to place BPMs inside them, but once in DTL tank 2, they are sufficiently long. There are two BPMs each in DTL tanks 2 through 6. Each BPM has equal-length 32 mm-long electrodes that subtend 60-deg. angles and with apertures equal to the normal 25-mm drift tube bore aperture. The electrodes and the housing are made of copper to match the normal drift tube material.

Of course the DTL tank is flooded with high power rf, and there is a concern that the rf will swamp any beam position signals. Simulations [5] with MAFIA [6] show that the rf interference is minimized to acceptable levels by placing the feedthrough ends of the shorted stripline electrodes in the centers of the drift tubes, as shown in Fig. 2. We further reduce the rf interference by processing the BPM signals at 805 MHz (the DTL tank frequency is 402.5 MHz). Right-angle Kaman SMA feedthroughs and Kapton-insulated coaxial cables are used to carry the signals up to the tops of the drift tube stems. To ensure good performance at high radiation levels, we replaced the PTFE (Teflon™) dielectric inside the SMA cable connectors at the drift tube end with polyimide (Vespel™), and we replaced the dielectric inside the SMA cable connectors at the top of the drift tube stem with polyethylene.
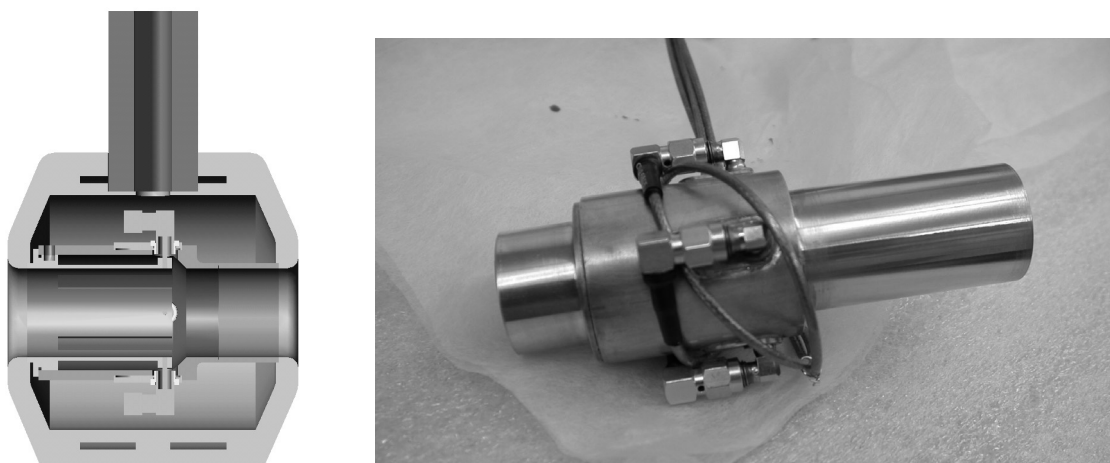
FIGURE 2. Left: cross section of a DTL BPM inside a drift tube. Right: photograph of a DTL BPM.

The signals are then transported to the equipment aisle on ¼-inch Heliax cables to a signal processor, which has three basic components – the analog front end (AFE), the digital front end (DFE), and the PCI motherboard. The motherboard, shown in Fig. 3, fits into a standard PCI slot in a rack mounted personal computer. The AFE downconverts the BPM signals to 50 MHz, then the DFE samples the resultant signals at 40 MHz to generate I/Q pairs. The digitized data is then uploaded into the PC memory and analyzed with a LabVIEW program to generate beam position and beam phase information. This data is then transferred to the EPICS operating system over an Ethernet link. In other locations in the SNS linac, such as the CCL and SCL, the processing occurs at 402.5 MHz to avoid interference from the 805 MHz rf used in these portions of the linac. Some specifications of the electronics are shown in Table 2. An example of some bench-test data for the electronics is shown in Fig. 4.

TABLE 2. Some specifications of the SNS BPM system.

Position accuracy	±1% of aperture radius
Position resolution	±0.1% of aperture radius
Phase accuracy	±2° of processing frequency
Phase resolution	±0.2° of processing frequency
Dynamic range	65 dB
Bandwidth	5 MHz

The first real-life use of the electronics occurred in April 2002 during the Front End Systems tests at Lawrence Berkeley National Laboratory (LBNL), where the SNS ion source, RFQ, and MEBT were designed and built. The first DTL BPM pickups will not see any beam until late 2003. However, tests with full power rf in DTL tank 3 are planned for November 2002 to test the rf interference.
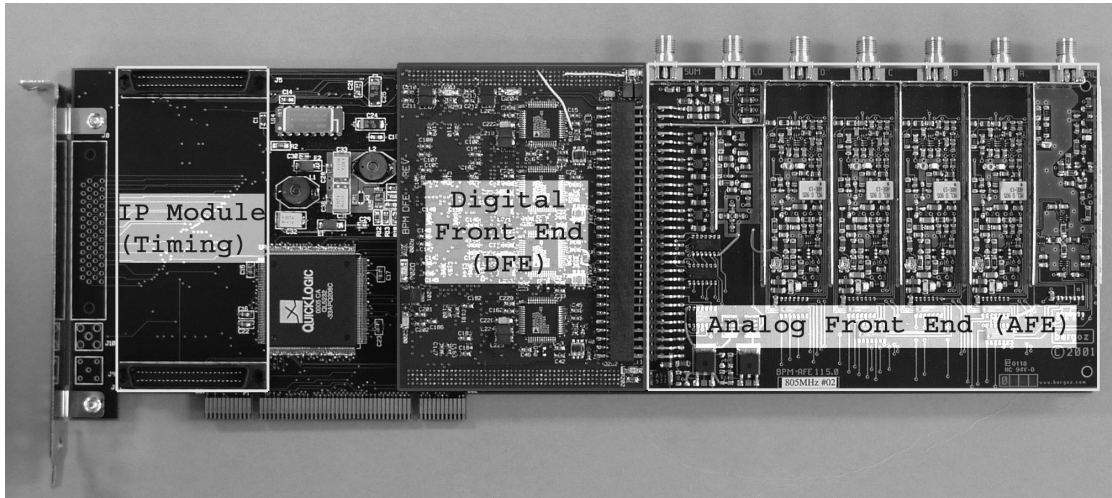
FIGURE 3. Photograph of a BPM PCI card, with AFE and DFE daughter cards.
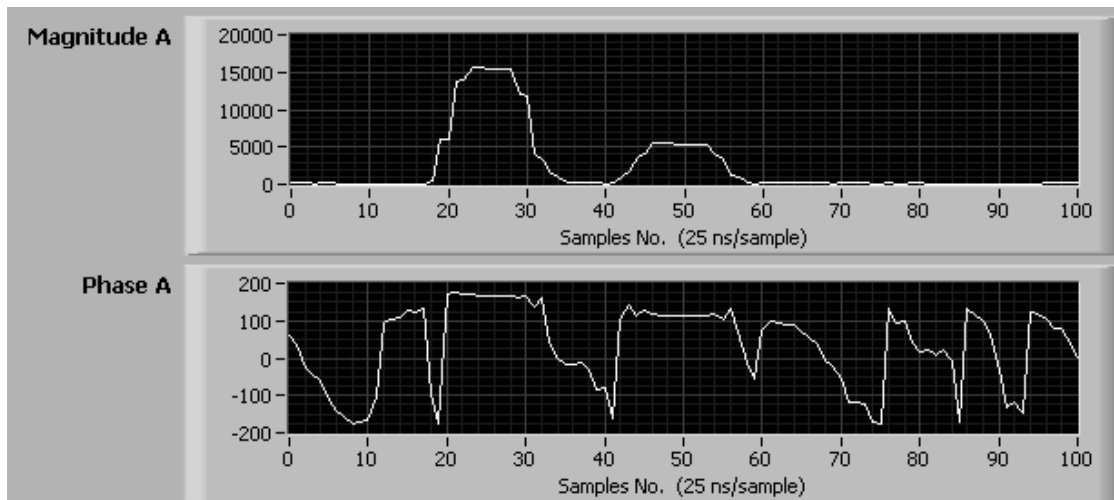

FIGURE 4. Example of some bench test data for the BPM electronics. Top trace: the self calibration pulse is injected first into the electronics, then into the cable. The amplitude difference of the two peaks is a measure of the cable loss and the time difference is a measure of the cable length. Bottom trace: phase measurement (data are valid only when the top trace is non zero).

THE SCL WS SYSTEM

The superconducting portion of the SNS linac has 23 cryomodules each containing three or four 6-cell rf cavities (there is room in the beam tunnel for 9 additional cryomodules for future upgrades). Between each cryomodule is a 1.6-m long warm inter-segment region that contains two quadrupole magnets, a vacuum pump, a BPM, and a wire scanner mounted on a vacuum box. Due to the close proximity to the superconducting rf cavities, any component in the inter-segment region must be compatible with the 10^{-9} Torr vacuum system, must have a very low particulate count, and must be very reliable. Vacuum breaches and particulate migrations into the rf

cavities could potentially cause serious damage to them. Maintenance of any beam diagnostics is also very difficult, since any operation that requires opening the vacuum system may involve removing the entire inter-segment beam line to a clean room. All components must also be suitable for bake out at 250 $^{\circ}$C for four hours. Other wire scanner system requirements are shown in Table 3.

TABLE 3. Some specifications of the SNS WS system.

Width measurement accuracy	±10% when fitted with a shape
Min beam pulse width (MEBT, DTL, CCL)	50 μs
Min beam pulse width (SCL)	100 μs

To satisfy these requirements we chose a design [7] that employs a formed bellows. The usual welded bellows were deemed to be inherently difficult to clean and more likely to form vacuum leaks. The drawback to using formed bellows is their limited stroke, leading to bellows that would be impractically long in the usual linear actuator design. For this reason we chose a pivoting actuator, so that the wire scanner fork sweeps through a gentle 20-deg. arc as it passes through the beam, as shown in Fig. 5. The arc is small enough that it does not seriously degrade our ability to individually measure horizontal, vertical, and diagonal beam profiles. The bellows design was extensively modeled with the COSMOS computer program to optimize the material, the wall thickness, the convolution dimensions, and the length. Our model results were also verified by the bellows vendor. The final choice was a bellows 21-cm long, 0.1-mm thick, and made of 304L stainless steel.

As mentioned above, the H$^-$ beam is too intense to allow use of the wire scanners during full power operation. The duty factor must be cut back enough to prevent damage to the signal wires. We evaluated [8] 32-micron diameter carbon (the largest diameter commercially available), 20-micron diameter tungsten, and 125-micron diameter tungsten wires, and found that only the carbon wires will survive 100 μs beam pulses (the minimum requirement), and even then only for 10 Hz operation. Peak temperatures for 1 and 10 Hz operation are shown in Table 4 for critical points along the linac (a critical point is defined to be where the beam size and energy deposition per particle conspire to create the worst case wire heating for a particular region of the linac). These temperatures were computed with a computer model that includes the effects of both proton and electron energy deposition and a temperature-dependent heat capacity. Only radiative cooling is assumed. When carbon wires are used and the signal is taken off the wire (as opposed to measuring prompt radiation from wire-induced beam loss), the maximum temperature [9] is limited to 1,600 K due to thermionic emission currents.

We chose to measure beam profiles by measuring the current on the signal wire, so the wires are biased to about 100 V (either positive or negative) to control the secondary electrons. In most cases the wire will be negatively biased to drive off the secondary electrons, but in some cases it may be more favorable to positively bias the wire. An example of such a case is where the signal caused by secondary electron emission is almost exactly cancelled by H$^-$ particles stopping in the wire, which, for 32-micron diameter carbon wire, occurs at a beam energy around 2.2 MeV. The signal processor has been designed to accommodate either positive or negative biasing, and bi-polar wire signals.
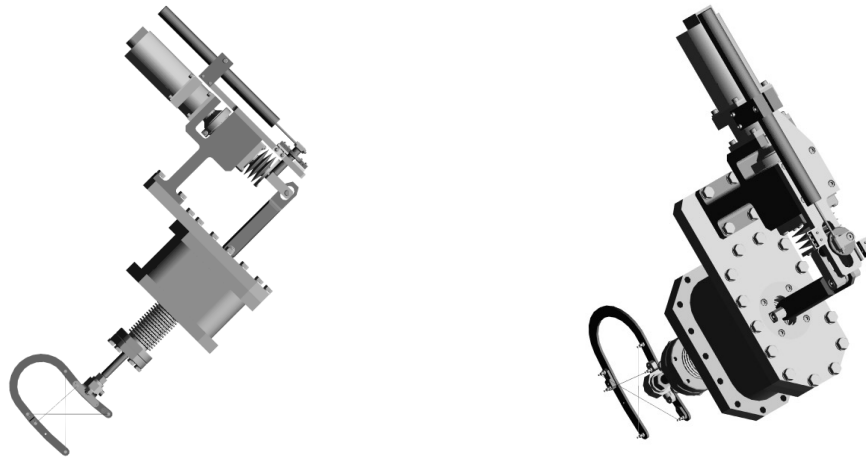
FIGURE 5. Left: side view of the SCL wire scanner actuator. Right: isometric view.

Three 32-micron diameter carbon wires are mounted on the wire scanner fork, offset from one another so that only one wire at a time will be within ±2 rms of the beam center. The third wire will be used to measure x-y correlations. The wires are mounted with a collet design developed for the LEDA experiment at LANL. They allow for a simple mounting system that keeps the wires under tension.

Location	Energy (MeV)	horiz. beam size (rms, cm)	vert. beam size (rms, cm)	Temp (^{o}C)	Temp (^{o}C)
TABLE 4. Some wire scanner signal wire temperatures at various critical points along the linac.					
MEBT[0]	2.5	0.09	0.16	1370[1]	
DTL 1	7.5	0.092	0.17	730[1]	1180[2]
DTL 2	22.9	0.086	0.15	530[1]	950[2]
DTL 3	39.8	0.10	0.11	530[1]	940[2]
DTL 4	56.5	0.073	0.13	580[1]	1010[2]
DTL 5	72.5	0.11	0.11	530[1]	940[2]
DTL 6	86.8	0.14	0.071	620[1]	1055[2]
CCL[3]	88 – 186	0.11	0.11	592[1]	1019[2]
SCL[4]	186 – 1000	0.16	0.16	320[5]	665[6]

[0]WS #5. [1]1 Hz, 50 us, 26 mA beam. [2]10 Hz, 50 us, 26 mA beam. [3]106 MeV. [4]200 MeV. [5]1 Hz, 100 us, 26 mA. [6]10 Hz, 100 us, 26 mA.

The accuracy of a beam size measurement depends in part on the positioning accuracy of the signal wire. We tested the actuator over a limited range of 4 mm (the range of the theodolite alignment system at our disposal), moving the actuator in both directions to include the backlash effects. The data showed less than ±0.13 mm of position error, which, together with the electronics error[*] is adequate to meet the requirement to measure the rms beam size with an accuracy of ±10%. We also cycled the actuator about 10,000 times to simulate 30 years of normal operation, and we did not observe any problems.

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[*] The error on each signal level measurement due to the electronics is less than 1% of the value of that measurement plus 2% of the signal level measured at the center of the beam.

As in the case of the BPM system, the wire scanner electronics is based on a custom-designed signal processor sampled by a PC running LabVIEW. The PC transmits the beam profiles to the EPICS control system over an Ethernet connection. The same PC also controls the motion of the actuator.

SUMMARY

The beam diagnostic challenges presented by the SNS linac primarily involve the high beam power and the constraints imposed by the superconducting rf cavities. Due to the limited space available in these workshop proceedings, we chose to focus on just two diagnostics systems of particular interest – the DTL BPM system and the SCL WS system. Both system designs are now complete. The DTL BPM fabrication is just finishing up, and the SCL WS actuator fabrication is just getting underway. Prototype electronics for both of these systems were tested at the LBL FES tests earlier this year and found to perform well. First beam through the DTL BPMs is expected around summer 2003, and first beam through the SCL WSs is expected around fall 2004.

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